Universitat de Lleida

Document downloaded from:

http://hdl.handle.net/10459.1/66467

The final publication is available at:

https://doi.org/10.1016/j.enbuild.2019.06.024

Copyright

cc-by-nc-nd, (c) Elsevier, 2019

Està subjecte a una llicència de Reconeixement-NoComercial-SenseObraDerivada 4.0 de Creative Commons

Modeling global and regional potentials for building-integrated solar energy generation

Ksenia Petrichenko[1], Diana Ürge-Vorsatz[2], Luisa F. Cabeza[3,*]

[1] Copenhagen Center On Energy Efficiency (C2E2), UNEP DTU Partnership, Danish Technological University (DTU), Marmorvej 51, Copenhagen, Denmark. Tel: +45 4533 5317. Email: ksepe@dtu.dk

[2] Center for Climate Change and Sustainable Energy Policy (3CSEP), Department of Environmental Sciences and Policy, Central European University (CEU), Nádor utca 9, 1051 Budapest, Hungary. Tel: +36-1-327-3021. Email: vorsatzd@ceu.hu

[3] GREiA Research Group, INSPIRES Research Centre, Universitat de Lleida, Pere de Cabrera s/n, 25001, Lleida, Spain. Tel: +34.973.00.35.77. Email: lcabeza@diei.udl.cat

*Corresponding author

Abstract

With the Paris Agreement coming into force, global efforts will need to maximize opportunities through energy efficiency and renewable energy generation. Zero energy/carbon initiatives are mushrooming worldwide, but it has not been fully understood which building types in which climates and under which conditions can potentially be built to net zero energy standards. In order to inform these efforts, a new model was developed to estimate the technical potential for building--integrated solar energy (BISE, the name of the model) generation in a high resolution regional, climate and building typology breakdown. , The BISE model also evaluates the opportunities for potential net zero energy buildings based on the BISE findigns, combining these with the findings of two global low-energy building models. The BISE model has a very high resolution in terms of geographic regions, climate types, building types and vintages. Moreover, the model combines methods for bottom-up energy modeling and geospatial analysis. The thermal building energy demand estimation is based on the 3CSEP-HEB model and the plug load scenarios are based on the BUENAS model. Results are wide, due to intrinsic limitationso of the model detailed in the paper, but it is shown that there is a substantial potential for building-integrated solar energy generation in all world regions, and that the Deep Efficiency Scenario allows significantly more building types to meet net zero energy levels by 2050in contrast to a scenario when only moderate energy efficiency improvements are implemented.

Keywords:

Solar energy; potentials; energy efficiency; net zero energy buildings; modeling; geospatial analysis

Nomenclature

AvF	Availability Factor
BIPV	Building Integrated Photovoltaics
BISE	Building Integrated Solar Energy
BUENAS	Bottom-Up Energy Analysis System
CDD	Cooling Degree Days
3CSEP-HEB	Higher Efficiency Building – Centre for Climate Change and Sustainable Energy Policy
E_{TH}	Thermal Energy
F_R	Heat Removal Factor
FA	Floor Area
GIS	Geographic Information System
HDD	Heating Degree Days
I_B	Beam solar Irradiation
I_D	Direct solar Irradiation
I_{glob}	Global solar Irradiation
I_T	Total solar Irradiation
INDC	Intended Nationally Determined Contribution
NZE	Net Zero Energy
PV	Photovoltaics
PV/T	Photovoltaic thermal
R_b	Ration of Beam radiation
RA	Roof Area
TOA	Top-Of-Atmosphere
U_L	Overall heat loss coeficient

Greek symbols

α	Absorptivity
β	System slope
η	Efficiency
ρ	Portion of global solar radiation reflected from the ground
τ	Transmittance

1. Introduction, Rationale and Aim

189 countries through their Intended Nationally Determined Contributions (INDCs) agreed to keep global warming “well under 2 degrees”, with an aspiration to maximize it at 1.5ºC, and balancing sources of greenhouse gas emissions with sinks for the second half of the century (COP21 2015). This requires an unprecedented effort at reducing energy-related emissions, too. 88 countries (including the European Union) specifically mentioned building and construction related actions in their NDCs (Dean et al. 2016). Buildings, being responsible for approximately one-third of global final energy use, are a key lever towards this effort, and are also among the areas where the deepest reductions are possible with limited sacrifice to service levels (Lucon et al. 2014). For instance, if visions towards dominantly net zero or energy plus buildings could be realized, this could relieve some burden from broad use of presently controversial negative emission technologies as such technologies are largely not included in integrated assessment models outlining global emissions pathways (UNEP 2016). As a result, net zero energy mandates and aspirations have been mushrooming worldwide. However, due to limited local renewable energy exposures and very diverse levels of energy demand, it is not well understood what share of global buildings can actually meet such ambitious goals.

Considering buildings as micro energy hubs[1], that are able to save, generate, store energy, and provide high quality energy services to the users, is hypothesized to offer a vast potential towards reaching ambitious climate targets. In addition, it helps in transitioning to more sustainable and reliable energy systems. Such approach presumes maximizing energy efficiency and increasing the on-site renewable energy generation with adequate energy storage capacities (De Groote and Fabbri 2016). Moreover, building integrated photovoltaics (BIPV) are recognized as systems with a significant potential to facilitate the energy transition towards renewable energy (Chang et al. 2019). BIPV can be implemented with PV or with PV/T. A hybrid PV/T solar system is a combination of photovoltaic (PV) panels and solar thermal (T) components. A PV/T system is a device that uses PV cells as a thermal absorber to convert electromagnetic radiation into electricity, while a solar thermal collector converts solar energy into heat and removes waste heat from the PV module. The aim of these components is to use the heat generated in the PV panel in order to generate not only electrical, but also thermal energy (Dupeyrat et al. 2011).

However, there is limited detailed understanding as for the global and regional opportunities and potentials offered by such building integrated solutions, as stated by Sulllivan et al. (2014), being the only one with global coverage that of Hoogwijk (2004), which will be comented in detail later in this paper.

The purpose of the creation of the BISE (Building Integrated Solar Energy) model, described in this paper, was to fill in this major knowledge gap: providing global and regional geospatially resolved high-granularity knowledge on the feasibility and potentials offered by very high energy efficiency buildings, combined with building-integrated renewable energy sources – i.e. how close can buildings become micro energy hubs; helping with the discourse on what share of the global building stock can aspire towards net zero energy standards.

[1] ‘A micro energy-hub can be considered as a building or a group of buildings exibly connected and synchronised with an energy system, being able to produce, store and/or consume energy efficiently’ (De Groote and Fabbri 2016).

Solar energy systems are currently the most widely installed renewable energy systems in the building sector in an effort to move towards net zero energy (NZE) level of building energy performance (Tsalikis and Martinopoulos 2015). However, to the date the understanding of the quantitative potential for the synergetic effect between building energy efficiency and building-integrated solar energy generation remains limited, especially on the large scale.

The model presented in this paper provides the opportunity to evaluate the feasibility of zero energy (or energy plus) buildings globally at a very high geospatial resolution, as well as by detailed building typology, vintage, use, and urban vs. rural location. More concretely, this requires the calculation of the maximum possible technical potential for building-integrated solar energy generation for various regions with the precision appropriate for an individual solar system.

According to Voivontas et al. (1998) cited in Mondal and Denich (2010), technical potential for renewable energy sources can be defined as "the amount of energy that can be exploited using existing technologies and thus depends on the time point of assessment". From this definition it follows that technical potential includes neither evaluation of the probability for this potential realization nor the costs of such realization.

The BISE model presented in this paper is novel from several perspectives. First, there is no similar estimation of the technical building-integrated solar energy potential at the global and regional scale. Adding a high level geospatial resolution to this pioneers further new ground. Evaluating the feasibility of net zero energy buildings per building type, end-use, vintage, urban/rural areas is rare even on a local basis, while the BISE model provides this analysis at a high-resolution global basis.

The model is extremely complex and a broad range of results has been generated. Therefore, this paper is the first in a series to describe the model methodology and its key high-level outputs. The purpose of this particular paper is mainly to present the overarching modeling logic, key assumptions, inputs, types of outputs the model can generate, and, finally, to provide a brief insight into a small selection of the key global findings.

2. Background: earlier estimates of building integrated solar energy potential

Most of the literature on building-integrated solar potential estimations focuses on photovoltaic (PV) technologies. However, the attempts to provide estimations at the global level are quite scarce and the sources usually narrow down the geographical scope to much smaller areas. For example, Gagnon et al. (2016) quantify the technical potential of photovoltaic (PV) systems deployed on all suitable areas of the rooftops in the continental United States. The authors used geographic information system (GIS) methods and PV-generation modeling to calculate the suitability of rooftops for hosting PV in 128 cities nationwide, subsequently extrapolating the estimates to the entire continental US California shows the greatest potential, with the opportunity to offset 74% of its electricity use in 2013 with rooftop PV, while for the whole US it is estimated that about 40% of its electricity needs can be covered through rooftop solar energy generation (Gagnon et al. 2016). A similar approach is followed by Jo and Otanicar (2011) to evaluate the potential PV electricity generation different governmental buildings in the Phoenix Metropolitan Area, showing that 10% of the total electricity consumption could be replaced by PV electricity. Similarly, Vulkan et al. (2018) developed a model to evaluate the potential of PV in residential buildings in dense urban areas, implementing it in Rishon LeZion, Israel.

A similar (LiDAR[2]) GIS method was applied to create the map of the New York city, which shows the solar energy potential for more than a million buildings in the city (Navarro 2011). The estimations presented on the map are produced by a computer model that calculates the incoming direct and diffuse solar radiation for every square meter of buildings rooftops in the City of New York, taking into account the position of the sun, overall atmospheric conditions, latitude, and shading (The New York City Solar America City Partnership 2016). Similar online tools estimating the potential for electricity generation from buildings rooftop PVs taking into account solar radiation, weather conditions, PV system area, tilt, orientation and potential shading, exist for Cambridge, Massachusetts (Mapdwell 2016) and Australia (APVI 2016).

Wiese et al. (2010) estimated technical potential of roof-tops for Austin Energy service area at the level of 3.3 million MWh per year. Leitelt (2010) presented results for Chapel Hill in the US, where potential annual energy output from PV installed at all available roof tops is 107,484 MWh. Castro et al. (2005) developed several scenarios for estimating potential solar electricity output from PV mounted on available roof areas in South region of the Iberian peninsula in Spain. According to the authors, by 2020 this region could produce 529 TJ of solar electricity under Moderate scenario, 937 TJ – under Normal scenario and 1875 TJ – under Ambitious scenario.

A few studies have explored the potential of solar water heating systems. Pillai and Banerjee (2007) calculated that the technical potential of solar water heating systems for the ‘synthetic area’ of Puna in India is 0.39 million lpd, which is equivalent to 6300 m^2 of collector area. Using 8005 municipalities of Spain as a geographical scope Izquierdo et al. (2011) estimated that roof-top solar water heating systems can supply1662 ktoe/yr of primary energy and 30.5 TWh/yr of total energy. The authors also estimated potential electricity output from roof-top PV at the level of 10 TWh/yr.

Tsalikis and Martinopoulos (2015) investigated solar energy potential of photovoltaic and solar thermal technologies in typical residential buildings in Greece, concluding that utilisation of a solar combi system for space and water heating, coupled with a small photovoltaic system can provide enough energy for getting close to the net zero energy balance.

As illustrated, most studies on building-integrated solar energy are local in coverage. We proceed by describing the global BISE model that represents the first global attempt at the detailed calculation of building-integrated solar energy potentials.

3. Methodology

The core of the methodology presented in this paper is the Building Integrated Solar Energy Model – BISE model – developed by the authors. The methodology presented in this paper combines estimation of technical potential for both solar thermal and solar electric energy generation. After a careful investigation by the first author, in order to investigate the maximal solar energy generation potential, the analysis focuses on the deployment of building-integrated hybrid photovoltaic thermal (PV/T) systems on a wide-scale across various regions and building types. The results for potential solar energy output are compared to estimated building energy demand,

[2] LiDAR stands for *Light Detection and Ranging.* It is a remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth. A LIDAR instrument principally consists of a laser, a scanner, and a specialized GPS receiver. Airplanes and helicopters are the most commonly used platforms for acquiring LIDAR data over broad areas (NOAA 2016)

significantly reduced through ambitious energy efficiency improvements, in order to assess the synergetic effect of high levels of buildings energy efficiency and solar energy generation in progressing towards net-zero energy or energy plus level of building energy performance. The following sections provide the details on the methodology of this analysis.

3.1. BISE model overview

The BISE model estimates the maximum technically possible solar energy generation by advanced technologies integrated into buildings. After careful investigations, the first author decided to focus on the hybrid photovoltaic and thermal (PV/T) solar energy technologies, described further later on, which allows for production of solar heat and solar electricity from the same receiving system surface. The model furthermore focuses on roof-integrated opporutnities, since walls provide much smaller potentials and are also less aesthetically accepted. Therefore, the main output of the model is the amount of solar heat and electricity, which can be produced on buildings roofs and utilized in buildings to meet energy demand for the main end-uses. It is assumed that solar heat can be used in buildings for space and water heating, while solar electricity can be used for meeting building energy demand for space cooling, lighting and appliances.

The BISE model allows for obtaining the results for different regions, climate zones, building types, building vintages and energy end-uses for each months of each year between 2005 and 2050, ensuring a high level of detail. In terms of regions, climate zones and building types the BISE model follows the same structure as High Efficiency Building (HEB) Model developed by Centre for Climate Change and Sustainable Energy Policy (3CSEP) (for further details on the methodology and input data for the 3CSEP-HEB model see Urge-Vorsatz et al. (2013), Urge-Vorsatz, Petrichenko et al. (2012)).

Eleven large regions are considered in the model, namely: North America, Western Europe, Eastern Europe, Former Soviet Union, Latin America, Middle East, Sub-Saharan Africa, South Asia, Centrally Planned Asia, Pacific OECD, and Other Pacific (for more details on definition of different regions see Urge-Vorsatz, Eyre, et al. 2012).

Within each region different climate zones are considered in order to capture the difference in building energy use and potential solar energy generation caused by climate variations. The differentiation among different climate zones is based on several climatic factors in terms their influence on building energy demand, namely: Heating Degree Days (HDD), Cooling Degree Days (CDD), relative humidity of the warmest month[3] (RH), and average temperature of the warmest month (T). The GIS spatial analysis tool and raster calculator technique were used to obtain this multiple-criteria climate classification with 17 climate zones and different combinations of the climate zones in each region (for more details on climate classification see Urge-Vorsatz, Petrichenko et al. 2012).

The BISE model distinguishes between urban, rural and slum areas of the built environment, as well as between residential and non-residential buildings. In urban areas residential buildings include single-family and multifamily buildings, while in rural areas only single-family buildings are assumed. Non-residential buildings are comprised of six sub-categories: hotels and restaurants, hospitals, educational, office, retail, and other buildings. The model also takes into account five building vintages in terms of different levels of building energy performance: existing/standard,

[3] July is assumed to be the warmest month for the Northern Hemisphere and January – for the Southern Hemisphere

new, retrofit, advanced new, and advanced retrofit buildings (for more details see Urge-Vorsatz, Petrichenko et al. 2012).

For each of these parameters (i.e. regions, climate zones, building types and vintages) the BISE model calculates potential solar thermal and solar electric outputs, which are compared to estimates of building energy demand for the respective end-uses, in order to analyze how much of the thermal and the electric demand can be met through solar energy generation. The estimates for building energy demand for different end-uses have been accessed from existing modeling products: namely 3CSEP High Efficiency Building (HEB) Model and Bottom-Up Energy Analysis System (BUENAS) Model (McNeil et al. 2012). 3CSEP HEB Model offers the results on energy use for space heating, cooling and water heating, while BUENAS Model gives the opportunity to derive the estimates on energy use for lighting and appliances.

Figure 1 illustrates the overall modeling logic of the analysis presented in this paper. As it can be seen from the Figure, input data for the model are mainly related to climatic and geographical parameters (different types of solar radiation, wind speed, ambient temperature, etc.), which are used for calculating solar energy outputs. Through a number of intermediate calculation steps the algorithm estimates hourly solar irradiation received by one square meter of the solar system, which is a key parameter for calculating solar thermal and electrical outputs from the solar systems.

As a separate process the roof area available for the installation of the solar technologies is calculated based on the estimations of the floor area from 3CSEP HEB model, roof-to-floor area factors resulted from the GIS analysis of the global urban built-up areas and roof availability factors found in the literature. The available roof area is calculated for each region, climate zone and building type.

At the next stage a number of technical parameters specific for a particular type of solar systems are taken into account in the calculations in order to estimate potential solar thermal energy supply and separately solar electric output.

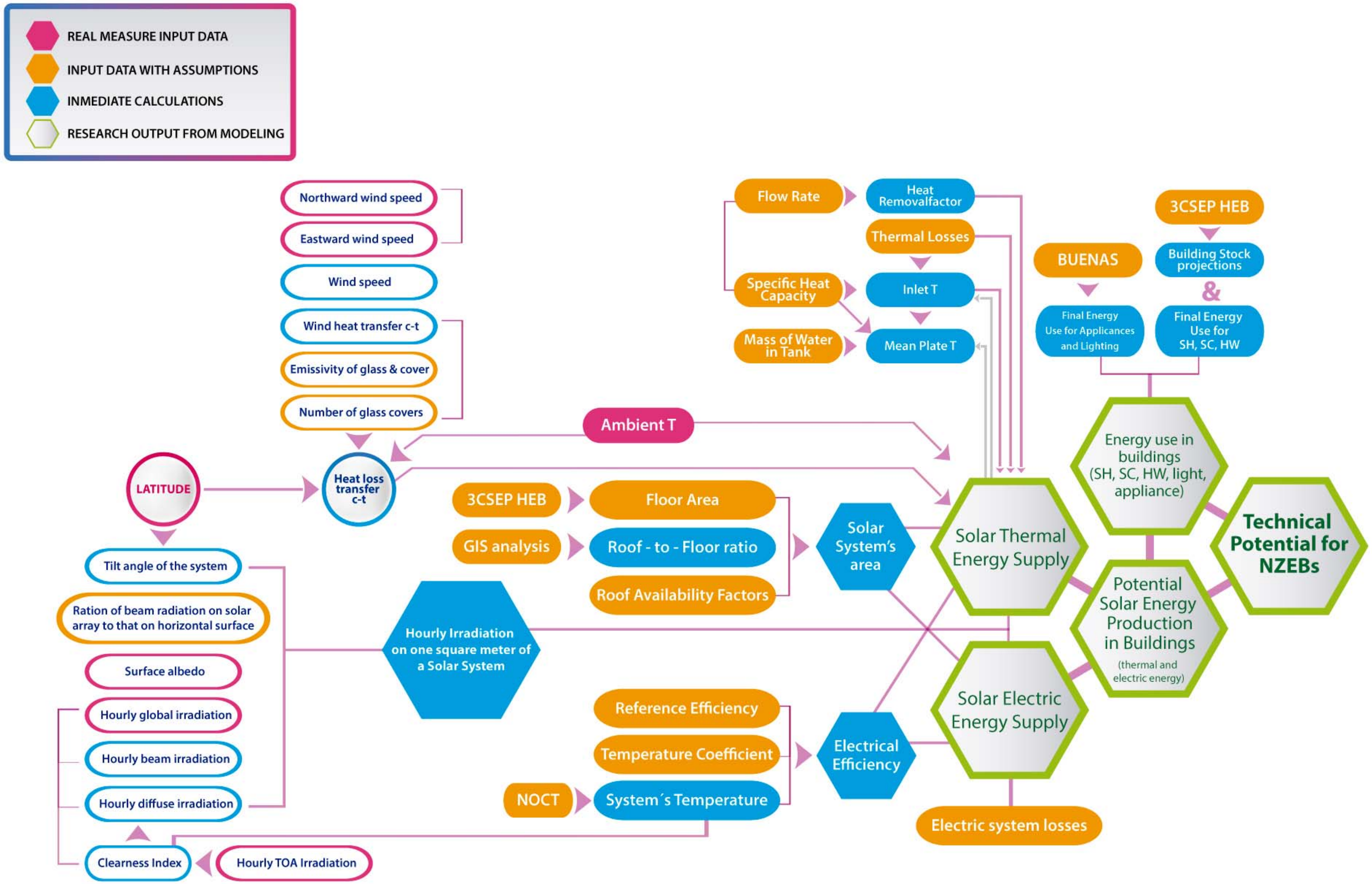

Figure 1. Schematic Map of Research Design

3.2. GIS analysis

Geospatial analysis is a crucial aspect of the BISE model. Geographic Information Systems (GIS) were developed as “tools for the storage, retrieval and display of geographic information” (Fortheringham and Rogerson 1994) and give the opportunity to “study and understand the real world processes by developing and applying manipulation, analysis criteria and models and to carry out integrated modeling” (Raju 2011).

For the purpose of the BISE model GIS analysis is used for two purposes:

1) Handling and processing the geospatial climatic datasets (see sub-section Input data below).
2) Deriving roof-to-floor ratios from the geospatial datasets on global urban built-up areas for calculating roof areas available for solar systems installations (Jackson et al. 2010).

For the second purpose the geospatial dataset containing the location of the areas with low, medium and high built-up densities within urban territories was obtained together with a generic Excel dataset, presenting various urban areas characteristics, and most importantly percentage of roof area for each type of built-up densities. From the geospatial data obtained the total urban built-up area was calculated for each region and urban area type by means of the spatial analysis zonal statistics of the ArcGIS software. Spatial analysis is one of the techniques used in GIS, which may be defined as “a general ability to manipulate spatial data into different forms and extract additional meaning as a result” (Fortheringham and Rogerson 1994).

Total roof areas were calculated using the data on roof area percentages of the built-up areas for each urban area type, assuming that they are the same for all climate zones within one region. Urban area types were then aligned with building types of the BISE model, based on the assumptions for the predominant type of buildings in each of the areas.

3.3. Calculation Procedures

The BISE algorithm consists of four main parts, and the key formulas for each of them are presented below.

The solar system area is calculated using the following equations:

- Roof area for each region and climate zone

$$RA = FA \times RF_{ratio}$$

where RA – roof area, FA – floor area, RF_{ratio} - roof-to-floor ratio

- Roof area available for solar systems installation for each region and climate zone

$$RA_{available} = RA \times AvF_f \times AvF_s$$

where $RA_{available}$ - roof area available for solar systems installation, AvF_s - availability factor to account for effects of shading, AvF_f - availability factor to account for effects of roof facilities

The hourly irradiation on the plane of the solar system array follows:

$$I_T = I_B R_b + I_D \left(\frac{1 + cos\beta}{2}\right) + I_{glob}\, \rho \left(\frac{1 - cos\beta}{2}\right)$$

where I_T - total solar radiation received by the solar system's surface, R_b is the ratio of beam radiation on the solar array to that on the horizontal surface, β is the system slope, depending on the latitude, I_B - beam radiation, I_D - diffuse radiation, I_{glob} - global radiation, $\frac{1+\cos\beta}{2}$ is a view factor to the sky, i.e the proportion of the sky that is visible from a given observer point (surface of the solar array) (Oke 1987); $\frac{1-\cos\beta}{2}$ is a view factor to the ground; and ρ is the portion of the global solar radiation reflected from the ground.

The electric solar energy supply has two parts:

- Electric efficiency of the solar system

$$\eta_{elec} = \eta_r \times (1 - \beta_p \times (T_c - T_r))$$

where η_r is the solar system electric efficiency at reference temperature T_r and β_p is the temperature coefficient for the system's efficiency. η_r and β_p depend on the type of solar system. T_c is the hourly solar system's surface temperature

- Electric energy output generated by one square meter of a solar system per hour

$$E_{EL\, output} = I_T \times \eta_{elec}$$

where η_{elec} - electrical efficiency of the solar system, I_T - the amount of total solar radiation received on the solar array. The output is further reduced to account for inverter efficiency and system losses

The thermal energy output generated by one square meter of a solar system per hour is calculated depending on a system configurations not the whole amount of I_T can be converted into thermal energy. Therefore, first, the output energy from one square meter of a solar system per hour is calculated ($E_{TH\, output}$), taking into acount the difference between the temperature of the working fluid entering the system and the ambient air temperature and the solar system characteristics:

$$E_{TH\, output} = F_R \times (I_T \times (\tau \cdot a - \tau \times \eta_{elec}) - U_L \times (T_{in} - T_a))$$

where $E_{TH\, output}$ - the output thermal energy from one square meter of a solar system per hour; F_R is the heat removal factor; τ is the transmittance of the cover; α is the shortwave absorptivity of the absorber; U_L is the overall heat loss coefficient of the collector; η_{elec} - electrical efficiency of the system; T_{in} – inlet fluid temperature; T_a – ambient temperature.

The parameters needed for the calculation of the electric solar energy supply are presented in Table **1**. For all these parameters some assumptions were made. As there is a vast number of PV module configurations on the market that can be integrated into PV/T, the assumption made in this study was to used the parameters for a typical Mono-Si PV module.

Table 1. Parameters for the calculation of the electric solar energy supply

Parameter	Assumed value	Reference
Reference temperature (T_r)	25ºC	RETScreen 2004
Temperature coefficient (β_p)	0.4%/ºC	RETScreen 2004
Reference efficiency (π_r)	13%	RETScreen 2004
Inverter efficiency (taking into account wiring losses) (η_{inver})	90%	Vardimon (2011)

3.4. Scenarios

Several scenarios of building energy use are considered in the BISE model. While estimations for solar energy potential per square meter of the available roof area do not significantly vary among scenarios, the building energy demand, which need to be covered, may differ significantly in different scenarios, reflecting different levels of building energy performance and energy efficiency improvements in buildings.

Scenarios considered in this paper are to a great extent built on those elaborated under the 3CSEP HEB Model. This model includes three main scenarios depending on the scale and ambition of energy efficiency improvements in buildings in different regions, namely: Deep, Moderate and Frozen Efficiency scenarios. A comprehensive description of 3CSEP HEB scenarios can be found in Urge-Vorsatz et al. (2013), Urge-Vorsatz, Petrichenko et al. (2012). For this paper Deep Efficiency scenario is the most important, as it presumes the most ambitious level of energy efficiency in respect to building shell related end-use, i.e. space heating, space cooling and water heating. Measures under this scenario are estimated to result in approximately 60-90% decrease in specific building energy use, which is a crucial step towards NZEBs. This scenario presumes that such measures are implemented on a large scale in both new and retrofit buildings across all the regions.

3.5. Input data

As was mentioned above and illustrated in Figure 1, the input data for the analysis presented in this paper come from several sources:

- Data for estimating hourly solar irradiation per unit solar system surface area include global hourly geo-spatial data for several clmatic parameters (see Figure 1), which have been obtained from NASA Science Mission Directorate, archived and distributed by the Goddard Earth Sciences (GES) Data and Information Services Centre (DISC) (NASA 2012).
- Data for available roof area for solar systems installations consist of the data on floor area for each region, climate zone, building type and building vintage estimated by 3CSEP HEB model and roof-to-floor factors estimated means of GIS analysis of the datasets for urban building areas described in Jackson et al. 2010.

- Data for building energy use for space heating, cooling and water heating come from 3CSEP HEB model.
- Data for energy use by appliances and lighting come from the BUENAS model.

The most important and complex part of the BISE model - estimation of solar thermal and electric energy supply – largely relies on the GIS analysis.

Geospatial data were derived from the Modern Era Retrospective Analysis for Research and Applications (MERRA) archive for every hour (from 00:30 till 23:30) of every day of the five years (2001 – 2005) for the following parameters: global irradiation (surface incident shortwave flux), top-of-atmosphere (TOA) irradiation (TOA incident shortwave flux), surface albedo, air temperature at 2 m above the displacement height, northward wind speed, and eastward wind speed[4]. For each of the seven parameters an average across the years was calculated (for each month, day and hour) resulting in the profile for an 'averaged' year in order to reduce potential weather abnormalities.

In order to handle a vast amount of data, reduce the risk of calculation errors and improve the robustness of the model, a customized software solution was developed in order to execute the calculation algorithm and visualize input data as well as each step of calculation in colorful dynamic maps with a global coverage, as well as to obtain the numerical results for each region, climate zone and building type stored into the multidimensional database.

3.6. Main assumptions

For its estimation of the maximum possible technical potential for building-integrated solar energy generation the BISE model focuses on hybrid photovoltaic/thermal solar technologies (PV/T).

In the BISE model it is assumed that PV/T technologies are installed on all available roof areas in buildings during construction or renovation process starting from the year 2014 and gradually becoming the standard for all retrofit and new buildings by 2025. Together with ambitious reduction in building energy use through energy efficiency improvement (as assumed by Deep Efficiency Scenario of 3CSEP-HEB Model) the results of BISE model give the opportunity to determine in which locations, climate zones and building types it is feasible to achieve NZE target by utilizing only solar energy.

It is assumed that the electrical and thermal energy generated by PV/T systems can be used in buildings during one month and, therefore, generated solar energy is compared to building energy use on a monthly basis.

In order to calculate the performance of solar systems on a large and aggregated scale the optimal tilt angle is assumed for all systems installations (OkSolar 2012).

Certain assumptions had to be made on the technical characteristics of solar PV/T systems. For the electric part values for a typical Mono-Si PV module are assumed, with the reference temperature of 25°C, reference efficiency of 13%, nominal operating cell temperature of 45°C and inverter efficiency of 90% (RETScreen 2004, Vardimon 2011). For the thermal part, values for a typical flat plate solar collector were assumed, namely: absorber plate emissivity of 0.93, glass emissivity of 0.9, efficiency factor of

[4] Northward wind speed and eastward wind speed represent two components of the wind, which have to be taken into account in calculating the overall wind speed

0.92, flow factor of 0.026 kg/s, transmittance of the cover of 0.9, absorptivity of the absorber of 0.94, mass of the water in the storage tank of 100 kg, heat transfer coefficient between the solar cells and the copper absorber – 20% and fixed thermal heat losses of 20% (Tripanagnostopoulos et al. 2000, Reynolds et al. 2004, Góngora-Gallardo et al. 2013, Matuska et al. 2009, Sok et al. 2009, Sok et al. 2010). The inlet fluid temperature (the temperature required in the storage tank) for the first hour of the sunlight was assumed constant (18°C) and the same across the regions, due to unavailability of such detailed measured data at the regional scale. The inlet temperature of the subsequent hours was calculated through an iterative process.

3.7. Modeling limitations

To the authors best knowledge, the methodology presented in this paper is the first attempt to model solar energy generation potential in buildings on the global and regional scales at the level of sophistication comparable to the models for individual buildings. Global and regional scale, however, required some compromises in terms of disregarding certain variations and details:

- **Scope**. The model focuses only on one type of renewable energy technology - building-integrated solar systems, focusing specifically on hybrid PV/T solar systems, as being one of the promising technologies, allowing for simultaneous generation of solar electricity and heat from the same receiving surface. There was no detailed assessment whether this technology is the most cost- or environmentally optimal in all climate zones and building types.
- **Input data**. Energy use estimations are taken from other models as the input data for the model. BUENAS model considers only a limited number of appliances, as well as the regional division and time horizon different from the ones of the BISE model, which required certain approximations. The data from the 3CSEP-HEB model also had to undergo some modifications in order to separate the estimations for final energy use for space heating and coolingbased on the heating and cooling degree days for each month.
- **Technical details**. Certain system-specific parameters for solar technologies (e.g. absorber plate emissivity, flow rate, efficiency factor, system losses, reference temperature of the system, reference efficiency of the PV part, etc.) were defined and assumed fixed based on the typical values found in the literature. Tilt angle of solar systems is assumed to be optimal in all the cases, as well as thermal and electric efficiencies of the system are assumed to be fixed during the modeling period in order to limit the model complexity.

4. Results

The results, which can be obtained from the model are extremely diverse and cover many areas. The final results for solar energy generation are obtained separately for potential solar electricity and solar heat for every hour of every month for an average year (in terms of weather data) between 2001 and 2005 and projected till 2050. The results can be aggregated on the hourly, daily, monthly and yearly basis, as well as presented for various regions (11 large regions, plus separately the US, China, India and 28 EU Member States), climate zones (up to 17 around the world), building types (single-family, multifamily, office, educational, hospital, retail and other buildings) and building vintages (existing, new, retrofit and energy efficient new and retrofit buildings).

There are also other types of the results, which can be obtained at intermediate steps of calculation, which include:

- Total roof area and roof area available for solar systems installations for each region, climate zone, building type and building vintage
- Hourly diffuse radiation per square meter of the horizontal surface[5]
- Hourly beam radiation per square meter of the horizontal surface [6]
- Hourly total solar radiation received by the plane of the solar system

Due to space constraints, in this paper we focus on selected high-level results only, while other papers will elaborate the detailed findings and policy implications. While the BISE model covers various residential and non-residential building types, due to space limitations this paper focuses only on the results for single-family and educational buildings for the illustration and comparison purposes.

Table 2 presents the potential for solar thermal and electric energy generation given by the BISE model at global and regional level.

Table 2. Global and regional potentials for solar thermal and electric energy generation in buildings under Deep Efficiency Scenario in 2050

Region/ Unit=PWh	Solar Thermal	Solar Electric
World	**6.9**	**7.2**
NAM – North America	1.4	0.9
SAS – South Asia	0.5	0.2
CPA – Central Planned Asia	1.8	1.3
WEU – Western Europe	0.9	0.5
EEU – Central and Eastern Europe	0.2	0.1
AFR – Sub-Saharian Africa	0.2	1.7
FSU – Former Soviet Union	0.6	0.2
LAM – Latin America	0.5	0.8
MEA – Nort Africa and Middle East	0.3	0.8
PAO – Oceania (Pacific OECD Countries)	0.3	0.2
PAS – Other Pacific Asia	0.2	0.5

Note: the numbers are based on the the aggregation of monthly results for different building types, taking into account building energy demand, i.e. as it is assumed in the model that solar energy can not be stored longer than for one month, any surplus of solar energy potential exceeding monthly building energy demand is not taken into account in this aggregation.

Figure 2 and Figure 3 present the results on the potential coverage of building energy needs by solar energy generation (separately for thermal and electric) in 2050 under

[5] Diffuse radiation is the solar radiation received from the Sun after its direction has been changed through scattering by the atmosphere
[6] Beam radiation is the solar radiation received from the Sun without been scattered by the atmosphere

Deep scenario for single-family residential and educational buildings, respectively. The figures demonstrate that In case of the solar thermal energy, the model identified a substantial potential to cover energy needs with solar energy for both building types during the warm season in most of the locations. The main reason for this is reduced heating load in buildings during this time period. Single-family buildings demonstrate the highest potential to cover thermal energy needs in all presented months. This difference is especially noticeable in the Northern Hemisphere in July, where for single-family buildings all thermal energy needs can be covered by solar energy, except for some Scandinavian countries, while for educational buildings this potential is far from reaching 100% in a number of locations (e.g. Canada, coldest part of Russia, mountainous areas of China, etc).

Results for January demonstrate that both building types have a clear need for axillary thermal energy supply in a large part of the Northern hemisphere. These results show the impact of climate conditions on the energy balance in buildings: coldest climates have the highest heating load, which is unlikely or impossible to cover solely with solar energy. Results for October show similar trends, although in most of locations the share of thermal energy use which can be covered by potential solar heat supply is larger than that in January, due to lower energy demand for space heating.

Buildings located in the Southern hemisphere typically have much higher potential to cover thermal energy needs with solar energy in comparison to the same building types from the other hemisphere. It can be explained by generally much lower energy demand for space heating and often for hot water, and at the same time a larger number of sunny hours throughout the year.

As for solar electricity the results are quite different from those for solar thermal energy outlined above. In single-family buildings it is possible to achieve 100% coverage for electric energy needs in a number of locations during the cold season. Exceptions are Canada, Europe and Australia due to high energy needs for lighting and appliances. Moreover, the first two regions have rather limited availability of solar energy resources during the winter, which decreases the opportunity to cover electrical needs to a full extent. Australia with a much higher availability of solar resources is characterized by notable cooling demand in January, which increases total need for electricity and, therefore, makes available solar electricity supply insufficient to cover all energy needs. In comparison to January in October more locations around the world demonstrate larger solar fraction, due to higher solar activity in the Northern hemisphere and lower demand for cooling in the Southern one.

During the summer-time the potential to get to net-zero through on-site solar energy generation in single-family buildings decreases in many regions in the Northern hemisphere (e.g. North America, Europe, Northern Africa, Middle East, etc.), as relatively high energy needs for lighting and appliances become accompanied by increased cooling loads.

Educational buildings typically demonstrate much lower potential to cover electricity needs with solar energy than single-family ones in all the months mainly due to relatively smaller available roof area in relation to high energy needs for appliances, lighting and cooling.

The results for this building type (Figure 3) for a number of regions show relatively low solar electric potential in most of the regions in the Northern part of the world with 5 - 30% solar fraction throughout the year. In the Southern hemisphere the solar fraction is higher than in the northern part of the world with a number of locations, for example, in India, Pacific and Africa demonstrating the potential to get close to the net zero energy level, especially in January and October.

Energy efficiency in buildings plays an important role for achieving higher solar fractions and potentially net zero energy building performance. The results presented in this paper analyse the 3CSEP-HEB Deep Efficiency Scenario – therefore a high level of energy efficiency in buildings is presumed for space heating, cooling and water heating. More detailed analysis on the importance of energy efficiency for the results of the BISE model can be found in Petrichenko (2015).

Climate conditions and time of the year also have significant impact on the solar fraction. Analysis of the monthly energy balances for selected months illustrates that different climate conditions influence both energy use and potential solar thermal and electric energy output. In heating-dominated climates the opportunity to cover thermal energy needs only with solar thermal energy supply is very limited. As for electric energy use and potential solar electricity production, climate zones with high cooling demand demonstrate more difficulties in reaching the NZE performance. Although cooling energy use in 2050 in a number of regions, climate zones and months has a relatively small share in the total electricity demand, during hot period of the year increased cooling demand in cooling-requiring climates often makes solar electricity output insufficient to cover all building electricity needs.

The results demonstrate that a significant technical potential for solar-supplied net-zero energy buildings exist on the global and regional scales. In a number of regions and building types it possible to achieve net- or nearly zero level of building energy performance especially for low- and medium-rise buildings.

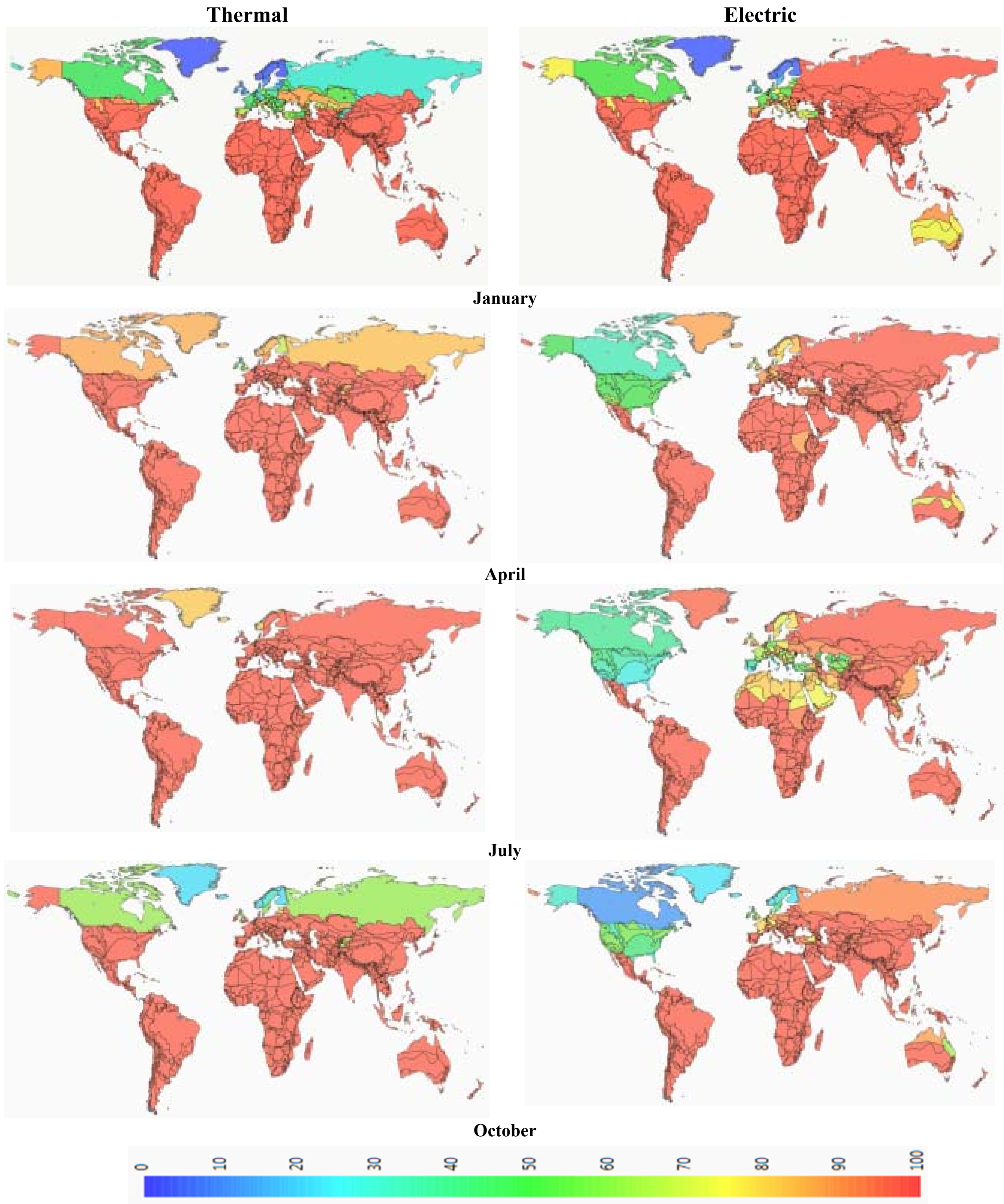

Figure 2. Potential for solar energy to cover building energy needs in 2050 under Deep scenario for single-family buildings. Left: thermal energy; right: total energy use

Note: the legend shows the percent of energy use, which can be covered by solar energy production

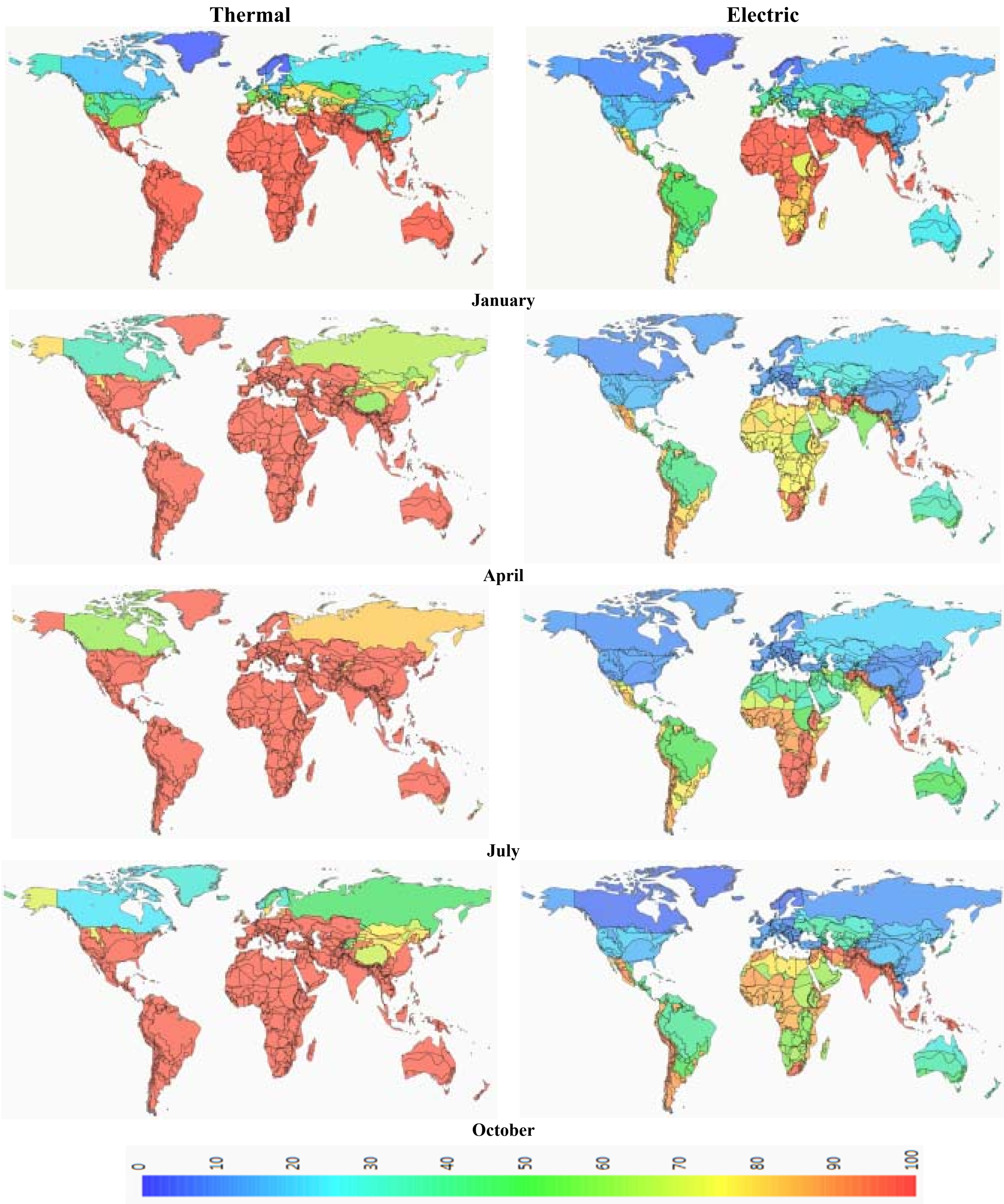

Figure 3. Potential for solar energy to cover building energy needs in 2050 under Deep scenario for educational buildings. Left: thermal energy; right: total energy use

Note: the legend shows the percent of energy use, which can be covered by solar energy production

5. Comparison with other model results

As mentioned above there are no similar studies in terms of the scope and detail, results of which can be directly compared to the estimations presented in this paper. The only study with a comparable geographical coverage but significantly less detail, which was found, is Hoogwijk (2004), which estimates technical potential of roof-integrated PV electricity generation. The author provides the results for 17 large regions, which to some extent can be aligned with 11 regions covered by BISE model. Moreover, Hoogwijk offers the estimates only for the base year (2001), while BISE model presumes a transition period for hypothetical proliferation of solar systems in the building sector between 2014 and 2025. Therefore, BISE model does not have the estimations for the solar potential in the Hoogwijk study base year. For the purpose of comparison technical potential for solar electricity from the BISE model has been estimated for the base year (2005) by calculating aggregated solar electric output per square meter of available roof area in 2050 and multiplying this ‘intensity’ by the available roof area in 2005 in each region. The results of this comparison by region can be seen in Figure 4. This figure shows that the results of the two assessments are at the same level of magnitude. Regions like Latin America, Former Soviet Union, South East Asia and Eastern Europe demonstrate quite similar results between the two studies. However, there are regions, in which results differ substantially (e.g. East Asia vs CPA, North+West+East+South Africa vs AFR, Europe OECD vs WEU, etc). In some cases it can be explained by the fact that the regions considered in the two models include different sets of countries. However, a more significant impact is likely to be made by the difference in the approach to estimating available roof areas for solar systems installation. Moreover, Hoogwijk’s study assumes a fixed PV efficiency, while BISE model is designed to take into account hourly, daily and monthly climatic variations in estimating the electrical efficiency of the solar systems for a given location of the globe.

At the global level the BISE model shows a slightly lower PV potential when compared to three other sources (see Figure 5). As can be seen in Figure 5 Hoogwijk and Sørensen arrived at very similar estimates, which can be explained by a number of similarities in their approach and assumptions. Hofman et.al. demonstrate the highest value for the potential solar electricity production among all four results mainly due to different approach to estimating the roof area and assumptions for PV efficiency (for more details see Hoogwijk 2004). In spite of having significantly different methodological approach from all three outlined studies BISE model presents very similar results to the ones provided in Hoogwijk (2004) and Sorensen (1999). BISE results are slightly lower, which can be explained by rather conservative estimations for available roof areas and more detailed calculation of electric efficiency, which can vary according to weather conditions and locations.

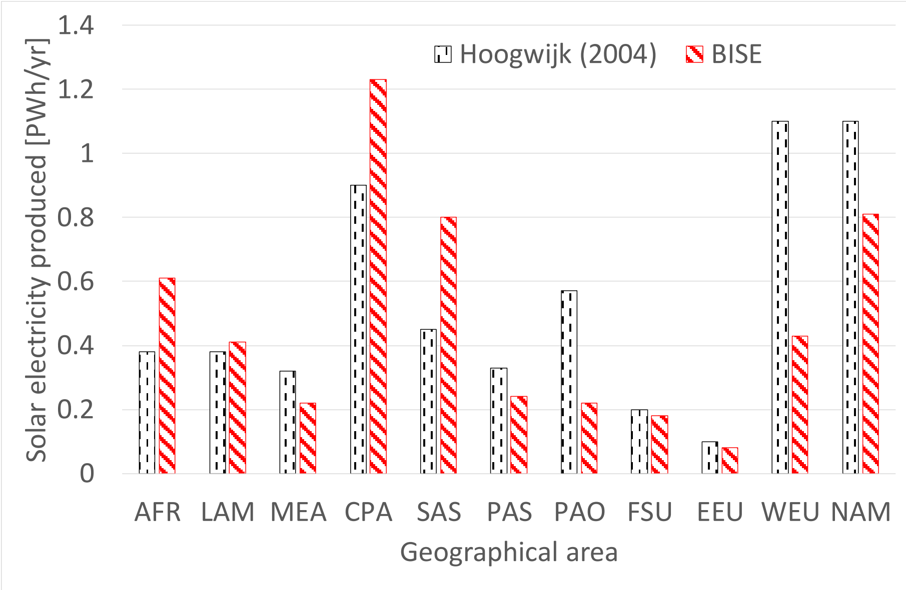

Figure 4. Results on the technical potential for solar electricity produced on building site in the base year: comparison between BISE model and estimations from Hoogwijk (2004).

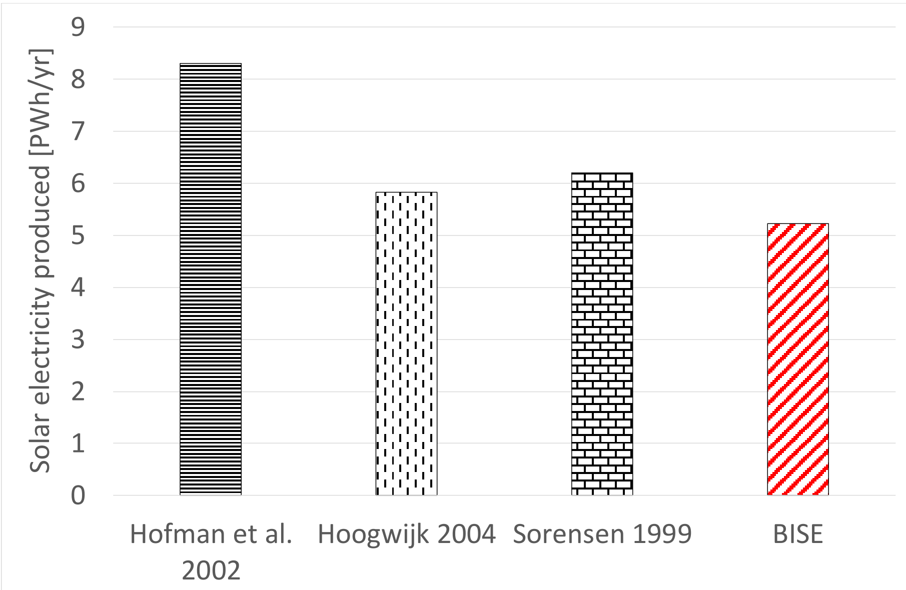

Figure 5. Comparison of the global technical potential for the annual roof-integrated PV electricity production between BISE model and three other studies

6. Conclusions

This paper presented the methodology and results of the global and regional model (BISE model) for estimating technical potential for net zero energy buildings in different locations, climates and building types through ambitious implementation of energy efficieincy measures and advanced building-integrated solar energy technologies.

The model combines methods of bottom-up energy modeling and geospatial analysis, which provides the opportunity to cover main end-uses, building typologies and geographically references climatic conditions. It applies methods of dynamic floor area estimations used in 3CSEP-HEB model and market diffusion utilized in the BUENAS model in order to derive results for building energy use for space heating, cooling, hot water and appliances and lighting, respectively. Based on these results a Deep Efficiency Scenario was constructed in order to reflect potential building energy use in case of world-wide application of energy efficient best-practices across end-uses and building types by 2050.

The results of Deep Efficiency Scenario demonstrated significant energy savings in all regions and building types in comparison to moderate energy efficiency improvements in buildings by 2050. Using high-resolution climatic data and spatial analysis techniques, the BISE model estimated how much electric and thermal solar energy can be generated from hybrid solar PV/T systems on the available roof areas.

In this paper the results for building energy use under the Deep Efficiency Scenario and technical solar energy potential were compared on monthly basis for 2050. This analysis demonstrated that there is a significant potential to achieve net zero-energy levels of building energy performance through energy efficiency measures and solar energy supply in a number of locations, building types and climates. High-rise buildings generally demonstrate lower potential for full coverage of building energy needs with solely onsite solar energy generation than low-rise buildings. This means that in densly built urban environments with mostly high-rise construction the solar energy supply option should be combined with other solutions for renewable energy supply.

Heating-dominated climates also demonstrate significant constraints in terms of reaching net-zero energy levels with solar technologies, as their application for space heating without auxilliary solutions (such as, for example, heat pumps) are still limited. In cooling-dominated climates cooling peak loads during the hot season often prevent some building types (mainly, non-residential) from geting to 'the net zero'.

Developing countries demonstrate mich higher potential for solar energy supply than the developed ones, mainly due to lower specific energy use and higher availability of solar energy resources in this locations. This finding shows an opportunity for developing countries to leapfrog to a more sustainable energy path for their building sectors.

This paper demonstrated that the technical potential is significant, however, it requires substantial policy effort to ensure a large-scale deployment of energy efficiency and solar energy options. It also does not analyze the economic feasibility of such deployment, as well as potential utilization of alternative technologies for renewable energy supply, which are beyond the scope of the paper, but are important directions for further research.

Acknowledgements

The work presented in this paper was funded by Central European University as part of a PhD research and through other grants. Special gratitude is expressed Dr. M. McNeil for sharing the data and their expertise on building energy use and energy modelling.

The authors would like to thank Mr. D. Leiszen for his creative approach to developing software and visulisation parts of the model.

References

APVI. 2016. “Live Solar Potential Tool.” http://solar.maps.umn.edu/.

Castro, M., A. Delgado, F.J. Argul, A. Colmenar, F. Yeves, and J. Peire. 2005. “Grid-Connected PV Buildings: Analysis of Future Scenarios with an Example of Southern Spain.” Solar Energy 79 (1): 86–95. doi:10.1016/j.solener.2004.09.022.

Chang, R, Y Cao, Y Lu, V Shabunko. 2019. ”Should BIPV technologies be empowered by innovation policy mix to facilitate energy transitions? - Revealing stakeholders' different perspectives using Q methodology.” Energy Policy 129: 307-18. doi: 10.1016/j.enpol.2019.02.047

COP21. 2015. “Adoption of the Paris Agreement.” United Nations Framework Convention on Climate Change. https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf.

De Groote, M, and M Fabbri. 2016. “Smart Buildings in a Decarbonised Energy System. 10 Principles to Deliver Real Benefits for Europe’s Citizens.” Buildings Performance Institute Europe (BPIE). http://bpie.eu/publication/smart-buildings-in-a-decarbonised-energy-system/.

Dean, B, J Dulac, K Petrichenko, and P. Graham. 2016. “Towards Zero-Emission Efficient and Resilient Buildings. Global Status Report.” Global Alliance for Buildings and Construction. http://kms.energyefficiencycentre.org/publication-report/global-status-report-2016-towards-zero-emission-efficient-and-resilient-buildings.

Dupeyrat, P, C Ménézo, M Rommel, and H Henning. 2011. “Efficient Single Glazed Flat Plate Photovoltaic–thermal Hybrid Collector for Domestic Hot Water System.” Solar Energy 85 (7): 1457–68. doi:10.1016/j.solener.2011.04.002.

Fortheringham, S, and P Rogerson, eds. 1994. Spatial Analysis and GIS. Technical Issues in Geographic Information Sysytems. Great Britain, London: Taylor & Francis Ltd.

Gagnon, P, R Margolis, J Melius, C Phillips, and R Elmore. 2016. “Rooftop Solar Photovoltaic Technical Potential in the United States: A Detailed Assessment.” Technical Report. National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy16osti/65298.pdf.

Góngora-Gallardo, G., M. Castro-Gil, A. Colmenar-Santos, and Mohamed Tawfik. 2013. “Efficiency Factors of Solar Collectors of Parallel Plates for Water.” Solar Energy 94 (August): 335–43. doi:10.1016/j.solener.2013.05.014.

Hoogwijk, M. 2004. “On the Global and Regional Potential of Renewable Energy Sources.” PhD dissertation, Utrecht, Netherlands: Universiteit Utrecht, Faculteit Scheikunde Proefschrift Universiteit Utrecht.

Izquierdo, S, C Montanes, C Dopazo, and N Fueyo. 2011. “Roof-Top Solar Energy Potential under Performance-Based Building Energy Codes: The Case of Spain.” Solar Energy 85 (1): 208–13. doi:doi: DOI: 10.1016/j.solener.2010.11.003.

Jackson, T.L, J.J Feddema, K.W Oleson, G.B Bonan, and J.T Bauer. 2010. “Parameterization Od Urban Characteristics for Global Climate Modeling.” Annals of the Association of American Geographers 100 (4): 848–65.

Jo, J.Hl, T.P Otanicar. 2011. ”A hierarchical methodology for the mesoscale assessment of building integrated roof solar energy systems.” Renewable Energy 36:2992-3000. doi: 10.1016/j.renene.2011.03.038

Leitelt, L.R. 2010. “Developing a Solar Energy Potential Map for Chapel Hill, NC.” Chapel Hill, NC, US: The faculty of the University of North Carolina at Chapel Hill.

Lucon O., D. Ürge-Vorsatz, A. Zain Ahmed, H. Akbari, P. Bertoldi, L. F. Cabeza, N. Eyre, A. Gadgil, L. D. D. Harvey, Y. Jiang, E. Liphoto, S. Mirasgedis, S. Murakami, J. Parikh, C. Pyke, and M. V. Vilariño, 2014: Buildings. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Mapdwell. 2016. “Cambridge Solar Map.” Massachusetts Institute of Technology (M.I.T.). https://www.mapdwell.com/en/solar.

Matuska, T, V Zmrhal, and J Metzger. 2009. “Detailed Modeling of Solar Flat-Plate Collectors with Design Tool Kolektor 2.2.” In Building Simulation 2009. Glasgow, Scotland. http://www.ibpsa.org/proceedings/bs2009/bs09_2289_2296.pdf.

McNeil, M, V.E Letschert, S de la Rue du Can, and J Ke. 2012. “Bottom-Up Energy Analysis System - Methodology and Results.” In Partnership with The Collaborative Labeling and Appliance Standards Program (CLASP). Berkeley, CA, US: Lawrence Berkeley National Laboratory.

Mondal, Md. A.H, and M Denich. 2010. “Assessment of Renewable Energy Resources Potential for Electricity Generation in Bangladesh.” Renewable and Sustainable Energy Reviews 14 (8): 2401–13. doi:10.1016/j.rser.2010.05.006.

NASA. 2012. “MDISC Data Subset.” Goddard Earth Sciences Data and Information Services Center. http://disc.sci.gsfc.nasa.gov/daac-bin/FTPSubset.pl.

Navarro, M. 2011. “Mapping Sun’s Potential to Power New York.” The New York Times, June 16. http://www.nytimes.com/2011/06/16/science/earth/16solar.html?_r=0.

NOAA. 2016. “What Is LIDAR?” National Oceanic and Atmospheric Administration. http://oceanservice.noaa.gov/facts/lidar.html.

Oke, T.R. 1987. Boundary Layer Climates. 2nd ed. London, New York: Methuen.

OkSolar. 2012. “Angle of Orientation for Solar Panels & Photovoltaic Modules.” Clean Energy for the 21st Century. http://www.oksolar.com/technical/angle_orientation.html.

Petrichenko, K. 2015. “Duet of Solar Energy and Energy Efficiency and Its Role for Net Zero Energy Buildings.” In First Fuel Now. Belambra Presqu’île de Giens, France: European Council for an Energy Efficient Economy.

Pillai, I.R., and R. Banerjee. 2007. “Methodology for Estimation of Potential for Solar Water Heating in a Target Area.” Solar Energy 81 (2): 162–72. doi:10.1016/j.solener.2006.04.009.

Raju, P.L.N. 2011. “Spatial Data Analysis.” Dehra Dun, India: Indian Institute of Remote Sensing, Geoinformatics Division. Accessed April 22. http://www.wamis.org/agm/pubs/agm8/Paper-8.pdf.

RETScreen. 2004. “Photovoltaic Project Analysis Chapter.” In Clean Energy Project Analysis, Third edition. RETScreen® Engineering & Cases Textbook. Canada: Minister of Natural Resources Canada. www.retscreen.net.

Reynolds, D.J., M.J. Jance, M. Behnia, and G.L. Morrison. 2004. “An Experimental and Computational Study of the Heat Loss Characteristics of a Trapezoidal Cavity Absorber.” Solar World Congress 2001 76 (1–3): 229–34. doi:10.1016/j.solener.2003.01.001.

Sok, E, Y Zhuo, and S Wang. 2010. “Performance and Economic Evaluation of a Hybrid Photovoltaic/Thermal Solar System in Northern China.” World Academy of Science, Engineering and Technology 48. http://www.waset.org/journals/waset/v48/v48-34.pdf.

Sørensen, B. 1999. Long Term Scenarios for Global Energy Demand and Supply. Four Global Greenhouse Mitigation Scenarios. Denmark: Roskilde University.

Sullivan, P, K Eurek, and R Margolis. 2014. ”Advanced Methods for Incorporating Solar Energy Technologies into Electric Sector Capacity-expansion Models: Literature Review and Analysis”. Technical Report NREL/TP6A20-61185.

The New York City Solar America City Partnership. 2016. “New York City Solar Map.” http://nycsolarmap.com/.

Tripanagnostopoulos, Y, M Souliotis, and Th Nousia. 2000. “Solar Collectors with Colored Absorbers.” Solar Energy 68 (4): 343–56. doi:10.1016/S0038-092X(00)00031-1.

Tsalikis, G, and G Martinopoulos. 2015. “Solar Energy Systems Potential for Nearly Net Zero Energy Residential Buildings.” Solar Energy 115 (May): 743–56. doi:10.1016/j.solener.2015.03.037.

UNEP. 2016. “The Emissions Gap Report 2016.” A UNEP Synthesis Report. Nairobi, Kenya: United Nations Environment Programme (UNEP). http://uneplive.unep.org/media/docs/theme/13/Emissions_Gap_Report_2016.pdf.

Urge-Vorsatz, D., N. Eyre, P. Graham, C. Kornevall, L.D.D. Harvey, M. Majumdar, M. McMahon, S. Mirasgedis, S. Murakami, and A. Novikova. 2012. “Towards Sustainable Energy End-Use: Buildings.” In Global Energy Assessment. Vol. Chapter 10. Laxenburg, Austria, Cambridge, United Kingdom and New York, NY, USA.: IIASA and Cambridge University Press.

Urge-Vorsatz, D., K Petrichenko, M Antal, M Staniec, M Labelle, E Ozden, and E Labzina. 2012. “Best Practice Policies for Low Energy and Carbon Buildings. A Scenario Analysis.” Budapest, Hungary: Research report prepared by the Center for Climate Change and Sustainable Policy (3CSEP) for the Global Best Practice Network for Buildings. http://www.globalbuildings.org/global-projects/.

Urge-Vorsatz, D., K Petrichenko, M Staniec, and J Eom. 2013. “Energy Use in Buildings in a Long-Term Perspective.” Current Opinion in Environmental Sustainability 5 (2): 141–51.

Vardimon, R. 2011. “Assessment of the Potential for Distributed Photovoltaic Electricity Production in Israel.” Renewable Energy 36 (2): 591–94. doi:10.1016/j.renene.2010.07.030.

Voivontas, D., D. Assimacopoulos, A. Mourelatos, and J. Corominas. 1998. “Evaluation of Renewable Energy Potential Using a GIS Decision Support System.” Renewable Energy 13 (3): 333–44. doi:10.1016/S0960-1481(98)00006-8.

Vuldkan, A., I Kloog, M Dorman, and E Erell. 2018. ”Modellling the potential for PV installation in residential buildings in dense urban areas”. Energy and Buildings 169:97-100. doi:10.1016/j.enbuild.2018.03.052

Wiese, S, L Libby, E Long, and B Ryan. 2010. “A Solar Rooftop Assessment for Austin.” In SOLAR 2010 Conference Proceedings. American Solar Energy Society.